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Biosensing by Differential Si Ring Resonators Robust to Process Variations

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Abstract

We have experimentally confirmed the validity of the robustness of the differential Si ring resonator biosensors, where the sensitivity is constant irrespective of the scattering of the resonance wavelength. Many differential sensors have been fabricated with different spaces between the rings and the output scattering characteristics were evaluated. Then the sucrose and prostate specific antigen (PSA) were measured and the practical sensitivity of 0.5 ng/ml for PSA was obtained.

1. Introduction

We have been studying biosensors detectable plural kinds of reactions rapidly without labeling [1,2]. Cascade type of differential biosensor is studied in other laboratory [3], but, parallel type is not studied. The schematic structure of the target integrated biosensor is shown in Fig. 1. The Si ring biosensor is compact and suitable for the integration. However, the sensitivity for biosensing was not sufficiently high and the improvement by using slot waveguide has been tried [4]. We have proposed the differential Si ring resonator biosensors whose sensitivity is high and constant irrespective of the scattering of the resonance wavelength of the constituent pair of rings [5]. In order to confirm the proposal, many differential sensors have been fabricated with different spaces between the rings and evaluated. As a result the validity of the proposal was proved. The sucrose and prostate specific antigen were measured.

2. Principle of Differential Biosensor with Robustness

Figure 2(a) shows the structure of the differential biosensor where the one output is connected to the other output through π phase shifter. An example of the simulation is shown in Fig. 2(b). The scattering of the resonance wavelength between the pair of rings is a serious problem because it causes the initial differential output. However, it was found that the scattering of the resonance wavelength is not at random but systematically changed as shown in Fig. 3 as a function of the position on the wafer depending on the distance between the rings [5]. The simulated output of the differential output (peak value) is shown in Fig. 4 as a function of the resonance wavelength difference $\Delta\lambda$ between the rings. It is found that the initial nonlinear part is followed by the linear part in the region 10^{-2} nm$< \Delta\lambda < 4\text{x}10^{-2}$ nm. When the operation point is set in the center of the linear part, by for example putting additional clad with different refractive index, the constant sensitivity is obtained for all the sensors because the sensitivity is given by the slope of this linear part [5].

3. Experimental

The samples were made by electron beam lithography and dry etching using silicon on insulator (SOI) wafer. The detailed fabrication process is in the previous paper [5]. The photographs of the fabricated sample are shown in Figs. 5(a) and 5(b). The schematic structure of the fluid channel is shown in Fig. 5(c) where the sample liquid is flown in the detection ring and the reference liquid is flown in the reference ring. For the investigation of the scattering of the differential output the fluid channel is not used and the π phase shifter is specially designed for the air ambient. For the actual sensing of sucrose and PSA the phase shifter and the rings are covered with SiO_2 cladding layer except by the windows to expose rings to the measurement liquid.

4. Results and Discussion

Figure 6(a) shows the scattering of the differential output of the samples with different distance between the rings (center to center). The average output and the deviation increase with the distance. These data are fitted to the Monte Carlo simulation result using the Gaussian distribution with average difference of the resonance wavelength $\Delta\lambda_\mu$ and the standard deviation σ. Here the measured maximum differential output of 3.5 nW was corresponded to the maximum simulation output of 0.9 in Fig. 4. The obtained $\Delta\lambda_\mu$ and σ are plotted as a function of the ring distance L in Fig. 6(b), both of them increases with L. $\Delta\lambda_\mu / L$ is 0.15 nm/mm which is difference of Fig. 3, maybe due to another SOI substrate. σ / L is 0.15 nm/mm. When L is between 100 μm and 250 μm the 4σ can be located to the linear part in Fig. 4, which means that the same sensitivity is obtained for the 95% of samples.

Finally we measured the sucrose and PSA solution. Figure 7(a) shows the result for the sucrose solution where 10^{-3}~10^{-2} % of sucrose can be detected and it well fits to the simulation. Figure 7(b) shows the result for PSA. First the reference and detection rings were sequentially exposed to Si-tag, ProteinG and IgG selectively combined with PSA by using the syringe. Then only the detection ring is exposed to PSA solution with various concentrations. The integrated output is changed at the PSA concentration of ~$5\text{x}10^{-10}$ g/ml, which is in the level of practical use. The result is replotted as a function of PSA concentration in Fig. 7(c), where the simulation result well fits to the experimental result.

5. Conclusion

We have confirmed the validity of the robustness of the differentia biosensor by initially differentiate the resonance wavelength of the rings. We have succeeded in detection of PSA in the practical sensitivity of 0.5 ng/ml.

Acknowledgement

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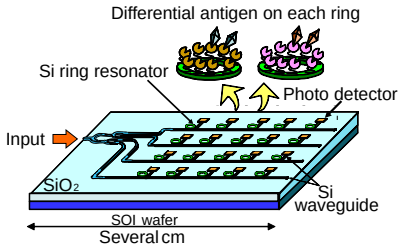

Fig. 1 Target integrated biosensor which provides simultaneous multispecies biosensing. Ring resonator sensors are suitable because of their compactness.

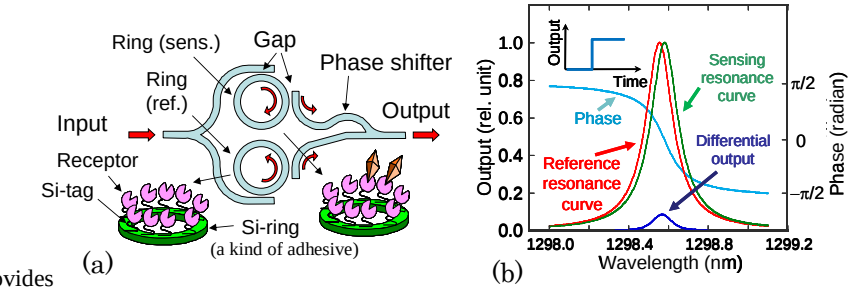

Fig. 2 (a) Structure of differential ring resonator sensor, and (b) its operation principle.

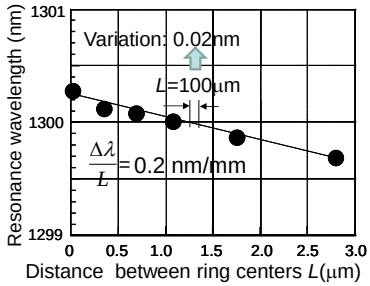

Fig. 3 The measurement result of the scattering of resonance wavelength, which is systematically varied depending on the distance between the rings at 0.2 nm/mm, here horizontal axis is the distance between the centers of the rings.

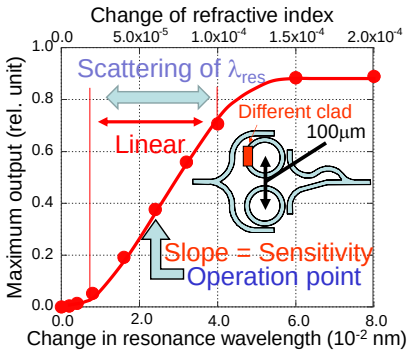

Fig. 4 The simulation result of output versus change in resonance wavelength between two rings. The output initially gradually increases and then it changes linearly and finally saturates.

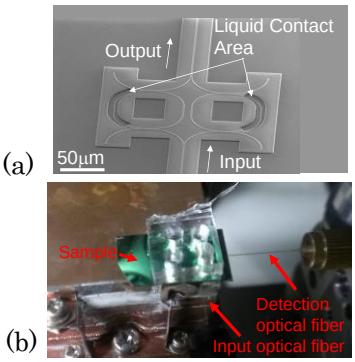

Fig. 5 (a) Scanning electron micrograph (SEM) picture of the fabricated differential ring resonator sensor with windows for liquid contact. (b) Photograph of additional flow channel biosensor.

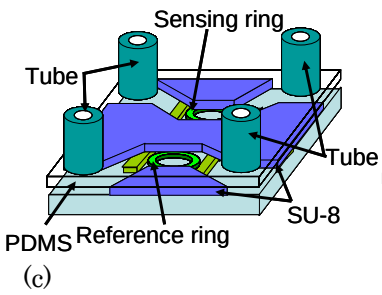

Fig. 5 (c) Schematic of additional flow channel biosensor.

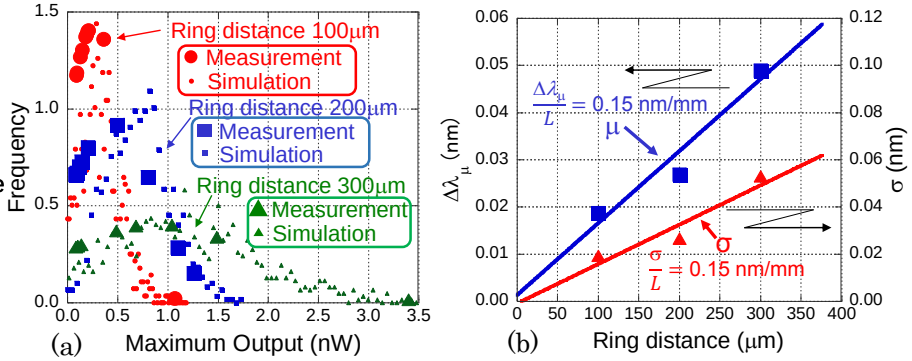

Fig. 6 (a) Scattering of the differential output of the samples with different distance between the pair of rings (center to center). (b) $\Delta\lambda_\mu$ and σ are plotted as a function of the ring distance L. $\Delta\lambda_\mu / L$ is 0.15 nm/mm which is difference of Fig. 3, maybe due to another SOI substrate.

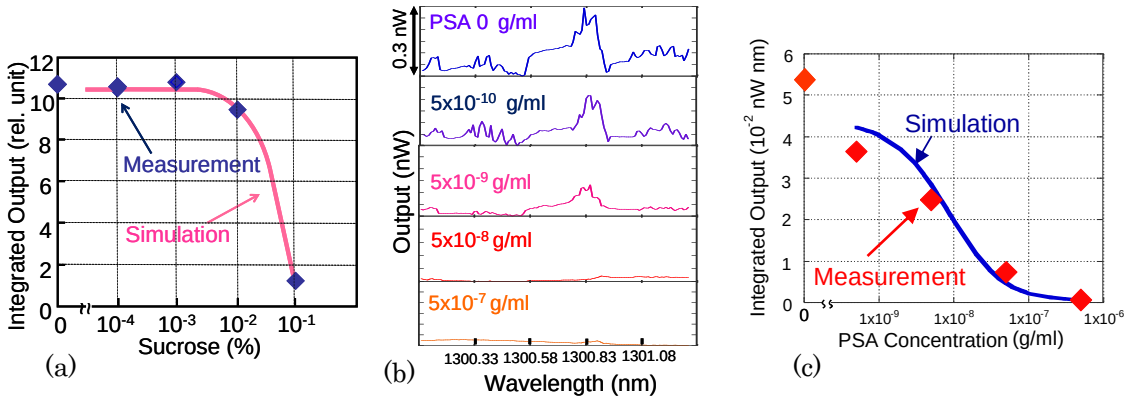

Fig. 7 (a) Output versus sucrose concentration with simulation. (b) Measured result of PSA detection, and (c) output versus PSA concentration with simulation.